WO9324237

Title:
METHOD AND APPARATUS FOR PRODUCING A LIQUID SPRAY

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : B05B 1/08	A1	(11) International Publication Number: WO 93/24237 (43) International Publication Date: 9 December 1993 (09.12.93)

(21) International Application Number: PCT/GB93/01089

(22) International Filing Date: 26 May 1993 (26.05.93)

(30) Priority data:
9211366.1 29 May 1992 (29.05.92) GB

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(81) Designated States: AT, AU, BB, BG, BR, BY, CA, CH, CZ, DE, DK, ES, FI, GB, HU, JP, KP, KR, KZ, LK, LU, MG, MN, MW, NL, NO, NZ, PL, PT, RO, RU, SD, SE, SK, UA, US, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

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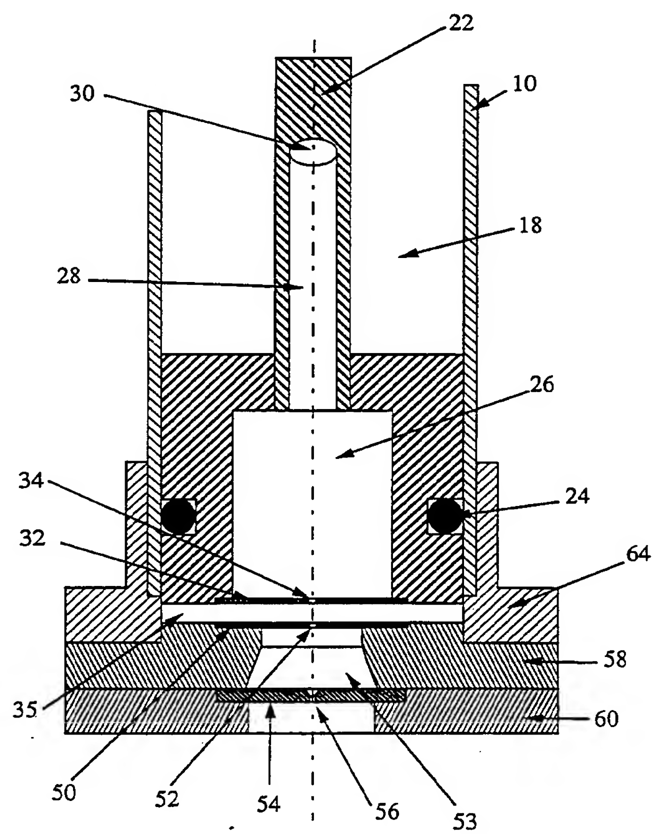

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METHOD AND APPARATUS FOR PRODUCING A LIQUID SPRAY

The invention relates to a method of and apparatus for the production of a liquid spray.

The production of a finely-divided liquid spray, or "atomisation" is at the heart of many products and processes including aerosols, crop sprayers, fuel injection systems and painting. The majority of these applications employ a nozzle through which liquid is forced whereupon it breaks up into droplets which vary in size over a wide range.

If the drop size can be controlled, significant advantages accrue. In aerosols, controlled drop size makes for uniform spray dispersion and coating. In agricultural spraying more regular drop size maximises the amount of liquid (be it insecticide, fungicide etc) reaching the targetted plants, whereas with an uncontrolled spray a large proportion of the liquid is dispersed by the wind through the drops being too small, or falls directly to the ground if the drops are too large. In fuel injectors, a more uniform spray offers the advantages of better, cleaner and more predictable combustion. In fire fighting, controlled drop size reduces the amount of water needed to put out a fire, by increasing the heat-absorbtion performance of the spray. Thus, in general, reducing the spread of drop sizes in a spray offers many benefits through an improved control of the spray properties. A few demanding applications such as ink jet printing require a very narrow spread of droplet sizes, termed "mono-dispersity".

In a conventional spray nozzle, the emergent jet of liquid breaks up into droplets either as a result of the formation of capillary waves, or due to shear stresses resulting from aerodynamic drag. With capillary-induced growth the droplet diameter is directly related to the wave length. When many different wave lengths are present, as is the case in conventional nozzles, many different droplet sizes are produced. Typically, 90% of the droplets lie in a region one decade wide say 10 to 100 microns.

The capillary waves are initiated by liquid borne noise generated by the liquid flow eg. by turbulence, vortex-shedding etc. In conventional nozzles, this noise is produced over a wide range of random frequencies which causes the initiation of capillary waves of many

different lengths. Those wave lengths close to an optimum value grow fastest with the result that the spread of droplet diameters is centred around the diameter corresponding to the optimum wave length.

Drag induced break up is a higher-energy process than the capillary wave mode, and also produces a wide range of drop sizes if uncontrolled. When the breakup is drag-induced, the process is characterised by the Weber number

$$W = d\rho V^2/\sigma$$

where d is the jet diameter, ρ the surrounding gas density, V the jet velocity and σ the surface tension of the liquid. For a jet break up in air, experimental studies have shown that the aerodynamic drag effect is minimal for $W \leq 5.3$ and the capillary wave process is dominant.

Conventional means of generating a controlled spray include an active element, such as a piezo-electric crystal or an electromechanical transducer, to break up the liquid by imparting energy to the liquid at an appropriate frequency. Thus, in some continuous ink jet printer nozzles, a high intensity single frequency acoustic signal is introduced to the liquid immediately upstream of the nozzle. The frequency of this signal is chosen to coincide with the optimum wavelength and the intensity is much greater than that of any other sources of noise in the flow. This produces mono-disperse droplets, although the piezo-electric transducer and electronics used to produce the acoustic signal are relatively expensive, and the operating environment is benign.

Providing and powering signal generation as part of a spray generator leads to complex and expensive apparatus requiring an electrical or other power supply, complicating the employment of such apparatus in environmentally demanding conditions and/or where the provision of energising power thereto is difficult or impracticable, for example to the nozzle of a fire fighting hose or in agricultural spraying apparatus where the spray generator may be mounted at the end of a spray boom remote from the carrying vehicle.

A form of acoustic spray generator which operates in a hostile environment is that used in some fuel burners for industrial and marine boilers. In these devices either the energy is imparted to the liquid

fuel before it exits the nozzle by means of a piezo-electric device as already described, or instead acoustic vibrations of a suitable frequency are provided in an air supply to the burner, and these vibrations impart energy to the liquid jet after it has left the nozzle to promote its break-up into a spray in which the spread of drop sizes is reduced. However, both of these devices have the disadvantage that energy must be supplied to the liquid from a external source, either electrically or from the air supply. The latter of course is only feasible if it is in any case required to mix the spray with air, and is not suitable for "airless" systems such as many paint-spraying systems.

The present invention has as an object the generation of a liquid spray of controlled droplet size which does not require an auxiliary power supply, or other external source of energy.

Thus, in one aspect the invention provides a method of generating a spray of liquid droplets comprising establishing a flow of the liquid, forming the flowing liquid into a jet, and subjecting the jet of liquid to vibrations of at least one predetermined frequency which promotes the break-up of the jet into droplets, characterised in that the energy for the vibrations is obtained from the liquid.

In another aspect the invention provides apparatus for generating a spray of liquid droplets comprising means for receiving a flow of liquid and for forming the liquid into a jet, and means for generating vibrations in the jet using energy obtained from the liquid, the vibrations being of at least one predetermined frequency such as to promote break-up of the jet into droplets.

Thus, in particular the energy may be obtained from the kinetic or pressure energy of the liquid.

The control of droplet size achieved by the invention for a given level of vibration energy is likely to be more marked with capillary-mode break up since the energy level of the natural break up process is lower than in the drag induced mode and the effect of the imparted vibration energy is thus relatively greater. However, benefits may still be expected when the invention is applied to a jet breaking up in the drag induced mode.

The vibrations preferably are generated by inducing acoustic

oscillations in the liquid flow, and (in some embodiments) as or before the liquid is formed into a jet.

Thus, the apparatus may comprise a nozzle for forming the jet and a hydrodynamic oscillator disposed upstream of the nozzle for generating the vibrations.

If a monodisperse spray is required then the vibrations should be a pure tone matching (ie. at or at least near to) the optimum break-up frequency of the liquid jet. However, it will be appreciated that for many applications control of the drop size in a narrower band than would naturally occur is adequate, and that true monodispersity is not required. In such circumstances it is not necessary to suppress all harmonics and sub-harmonics of the tone (vibration) generator, and indeed it may be appropriate deliberately to generate more than one predetermined frequency.

The means for generating vibrations may be such as to produce a substantially constant frequency, means being provided for adjusting the flow velocity of the liquid.

Optimum use of the apparatus may then be assisted by means for varying the flow rate of the liquid so as to match the break-up frequency (which is flow-rate dependent) to that of the tone generator. Alternatively, the means for generating vibrations may be such as to produce a predetermined frequency which varies with the flow velocity of the liquid.

This may have the advantage that the frequency may automatically be at or near the preferred break-up frequency over a range of flow rates, and may thereby produce a substantially constant drop size over a range of flow rates.

In another form of the invention there may be means (for example a tuned mechanical device) for extracting energy from the liquid flow and for reintroducing it into the liquid to generate the vibrations.

The means for forming the liquid into a jet may be at least partially defined by the tuned mechanical member, or by structure connected thereto.

The energy may be at least partially reintroduced in to the liquid via the air or other gas through which the liquid passes after being

formed into a jet.

Some embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 shows the relationship of natural capillary-wave jet break-up rate, jet diameter and frequency,

Figure 2 shows very diagrammatically one embodiment of the invention;

Figure 3 shows, also very diagrammatically another embodiment of the invention,

Figures 4 to 6 show in more detail apparatus of the same type as Figure 3, Figure 5 being an enlarged view of part of Figure 4, and Figure 6 being external views of the apparatus shown in section in Figure 4.

Figures 7 to 10, 12 and 13 show further devices for use in the invention and

Figure 11 shows a further embodiment of the invention.

The capillary-wave mode of break-up of a jet exiting from a nozzle will first be considered in two contexts, the natural disintegration of the jet, and the triggered (frequency-induced) disintegration of the jet.

The natural break-up of a liquid jet may be analysed by making the following simplifying assumptions:

a. the jet is taken to be of cylindrical cross section, diameter d.

b. the jet is assumed to disintegrate in a vacuum. That is to say that the influence of the gas surrounding the jet is negligible.

c. the flow in the jet is laminar so that the background disturbances in the flow are small and of random spectrum.

d. the break-up process is dominated by the exponential growth of axisymmetrical surface disturbances, termed varicose, of wavelength λ.

e. the flow is inviscid.

It has been shown that, subject to the limitation that the disturbance wavelength is larger than the jet circumference ($\lambda \geq \pi d$), then the growth rate of the axisymmetrical disturbance is given by

$$q^2 = 8\,\sigma / (\rho d^3) \quad (1-\gamma^2)\ I_1(\gamma)/I_0(\gamma)$$

where q is the exponential growth rate of the disturbance, σ and ρ the liquid surface tension and density, d the jet diameter, γ the non

dimensional wave number ($\gamma = \pi d/ \lambda$), and I_1, I_0 modified Bessel functions of the first kind.

By differentiation, a maximum for this equation in the range $0 \leq \quad \leq 1$ can be found:

$$qmax = 0.97 \sqrt{[\sigma/(\ d^3)]}$$

The foregoing equations assume an inviscid fluid. In practice in many applications the viscosity of water can be assumed to have negligible effect, and for water the corresponding wavelength is thus

$$\lambda max = 4.51 \ d$$

A similar analysis incorporating the effect of viscosity, leads to the following results:

$$q^2 + 12\mu\gamma^2/\varrho d^2 \ q - 4\sigma\gamma^2/\varrho d^3(1-\gamma^2) = 0$$

$$\text{and } qmax = \sqrt{(\ d^3/\sigma)} + 3\mu d/\sigma$$

The quadratic equation in q for the varicose growth rate coefficient is plotted on Figure 1 for liquids with different viscosity, with σ, ϱ and d/2 set to unity.

The jet breaks-up when the amplitude of the disturbance δ grows to equal the radius of the jet d/2. For controlled breakup, a suitable acoustic wave of frequency is introduced increasing the amplitude δ_0 of the disturbance at the nozzle. In the foregoing analysis, it is shown that there is a preferred wavelength of disturbance which is most amplified. For example, in water the relationships $v = f\lambda$ and $\lambda max = 4.51$ d fix the appropriate frequency f at:

$$fmax = 0.22 \ V/d$$

$$\text{or } fmax = 0.28 \ Q \ / \ d^3$$

where Q is the flow rate ($Q=\pi d^2V/4$).

If the nozzle diameter (d_n) is assumed to be the same as that of the jet (d) this expression can take the form of a nozzle Strouhal number:

$$S_n = fmax \ d_n/V = 0.22$$

$$\text{or } S_n' = fmaxd_n^3/Q = 0.28$$

However, this strict relationship can be relaxed due to the parabolic shape of the growth coefficient function as plotted on Figure 1. Provided the acoustic signal is significantly larger than the background disturbances, the excited frequency will still be amplified

strongly, and the larger value of δ_0 at fmax dominates the rest of the spectrum. This leads to a broader band of operational frequencies which can be used to produce controlled break-up. For example, published sources quote a useful range of operational wavelength to jet and nozzle diameter ratios of between 3.5 and 7.0:

$$3.5 \leq \lambda/d_n \leq 7$$

$$\text{or} \quad 0.14 \leq S_n \leq 0.29$$

The driving frequency f is tuned to satisfy this relationship, and therefore to trigger the break-up into drops forming at this same frequency. By considering the conservation of flux (liquid flow), we can establish the size of the produced drops.

The flux leaving the nozzle is:

$$\pi\, d_n^2\, V / 4$$

The flux carried by the monosized drop of diameter k is:

$$\pi\, k^3/6$$

which combined with $\lambda = V/f = 4.51d_n$

gives $d_n^2V/4 = fk^3/6$

from which $k = 1.89d$

Thus, for a given nozzle geometry operating at the ideal frequency fmax, the drop size produced by controlled jet break-up is fixed at 1.89 times the jet and nozzle diameter.

Experiments show that this analysis is only valid if the nozzle is driven at the correct frequency fmax. At the off design conditions, droplets of different sizes are produced, although the size variation is still less than with an uncontrolled spray. If the signal is strong enough with a frequency close to fmax, the drops can also take a stable pattern of a large drop of diameter k=1.89d, followed or preceded by a smaller "satellite" drop carrying the excess flow rate. Under those circumstances, monodispersion is not achieved, though bidispersion is. Two life histories are probable for a satellite drop in a spray discharged into free air. It can just recombine with its 'mother' drop, or it can be blown away. If the satellite drop has been produced closely behind the mother drop, its smaller aerodynamic drag in the larger drop wake will allow it to catch up and recombine with the mother drop, thereby producing a monosized stream of recombined droplets.

Conversely, the satellite drops can be blown away or removed using their different flight path, so that there remains a stream of monosized mother drops. Both solutions are less than optimum but again the result is superior to an uncontrolled spray.

In some circumstances a spray with a controlled range of drop sizes may be advantageous. For example in an IC engine, the production of small satellite drops may be advantageous to promote good combustion when the engine is cold, and could be achieved whilst maintaining the overall fuel/air ratio by controlling the injector flow rate and the injection period.

It will be appreciated the foregoing analysis is based upon linearized theory. It is therefore strictly restricted to infinitesimal disturbances, and is certainly no better than a first order approximation when considering large scale disturbances such as jet breakup. The appearance of the satellite drops is not predicted by this theory, nor is the precise value of the wavelength of the fastest growing disturbances. In this regard, experimental work is only in approximate agreement with theory. In general, experimental values of λ_{max}/d for liquids tend to be higher than the predicted value (4.51), varying between 3.5 and 7.0. Non linear analysis also shows theoretically that the wavelength of the most unstable disturbance is a function of the amplitude of the initially applied disturbance.

It will also be appreciated that the analysis is in the context of circular jets. Practical spray nozzles may however be configured to produce a variety of other shapes of jet, for example annular, conical or sheet (fan) shaped. Whilst the mathematical models of such systems are considerably more complicated than the foregoing, the apparatus for putting the concept into effect in all cases is relatively simple and is susceptible to routine experimental and empirical methods to arrive at a workable design using the teaching of this specification.

The preferred manner of subjecting the jet to vibrations is by inducing acoustic (pressure) oscillations in the liquid upstream of the jet in a resonant device. Such a device is effectively a hydrodynamic oscillator or whistle, although using liquid as its operating fluid rather than air.

Like other oscillators, whistles depend upon positive feed back and

can be conveniently divided in three classes based on their feedback mechanisms.

If the feedback energy consists of part of the unstable flow itself, the whistle can be placed in class I. These are mainly aeolian tone generators, such as telegraph wires, where the action of the vortex generated on one side of the generator triggers the shedding of a vortex on the other side. The interaction is entirely hydrodynamic, and only acts as a stabiliser of the process so that the sound intensity usually remains low. However the shape of the device makes it particularly suitable for use with elongated slot-shaped spray nozzles.

Thus in figure 2 a wire 1 is disposed transversely across a flow duct terminating in a slot-shaped nozzle 2. Vortices 3 are shed alternately from opposite sides of the wire, generating acoustic vibrations in the liquid and promoting break-up thereof when it issues from the nozzle as a flat jet 4.

If the feedback energy consists of the sound itself acting on the flow, the whistle is a class II whistle. Examples are edge tone, ring tone and in particular hole tone whistles. In a hole tone whistle shown very diagrammatically in Figure 3 two coaxial round holes 5, 5a are provided in axially spaced parallel thin plates, and the whistle sounds when the jet formed at the first hole 5 sheds vortices 7 which impinge on the plate containing the second hole 5a causing acoustic waves to propagate back towards the first hole where they help to trigger the shedding of new vortices. The sound feedback causes the vortices produced at hole 5 to be more periodic and in phase with one another, strengthening the generation process and promoting the break up of a jet 8 issuing from a nozzle 6. As will be explained later, the relationship between the diameter of the nozzle 6 and that of the holes 5, 5a, determines the extent to which the drop size is controlled.

In a Class III whistle the feedback loop is established either by a reflecting surface or by a resonator. Many reeded wind instruments rely on this principle. A resonant column of working fluid controls the final frequency of the generated tone, and thus a class III whistle generates a constant frequency independent of flow rate. Conversely, class I and II whistles are dominated by the generation mechanism so

that their tone frequency is dependent upon the flow velocity.

The whistle must include or at least be excited by a suitable source of acoustic vibrations.

In class I whistles, very little or no amplification occurs in the feedback loop so that an inherently strong signal has to be generated directly. This limits the sources to strong hydrodynamic variations or vortices.

In class II whistles, amplification occurs so that the initial signal can be much weaker, thereby extending the range of suitable sound generation mechanisms. In fact any white noise signal should be suitable, if the feedback mechanism is strong enough to control the source and the closed loop amplifying gain high enough. Sources of white noise signal in fluid are multiple, such as turbulent flow motion in a shear layer or in a jet, buffeting or separation induced vorticity.

The separation of types of feedback and generation mechanisms however in practice is less clear-cut.

Initial design choices should therefore be made on practical considerations such as manufacturability and operational robustness, whilst the derived acoustic performance of the design can be determined by experiment and the design thereafter modified accordingly. Readily manufactured whistles include hole tones, edge tones and reed based devices, and are susceptible to limited theoretical analysis using non-dimensional groups.

Referring to Figure 3, the holes 5, 5a each have a diameter dh and are spaced by a distance b. The axial length of the holes (ie. the plate thickness) is t, and the flow velocity through them is V.

The performance of the whistle is characterised inter alia by three non-dimensional Strouhal numbers:

Hole Strouhal Number

$$S_h=d_h\ f/nv$$

This group (n being a pure number) characterises the stable shedding of vortices by the hole 5, controlled by a weak class I feedback mechanism. This parameter would assume a single value if a single hole was used, and therefore represents the natural frequency of

the hole or hole Strouhal frequency.

Feedback Strouhal Number:

$$S_b = bf/nV$$

This group characterises the feedback mechanism of the whistle. The whistling frequency is a function of the time taken by the disturbance to travel downstream, amplify itself and feed back some of the energy into the source. Whatever model is assumed for the disturbance, the time taken for it to travel will always be a function of the flow speed V, the distance to travel b, and the speed of sound in the medium c. The time of travel can be modelled precisely by assuming that the disturbance is a vortex travelling at a known fraction of the jet velocity, or that it is a jet deformation which travels at the jet velocity. The feedback is assumed to be of class II so that upstream propagation is done at the speed of sound c. For low Mach number flow ($V/c \leq 0.2$), the feedback time can be regarded as negligible, and the Strouhal number becomes a true represention of the flow feedback mechanism.

Plate Strouhal Number:

$$S_t = tf/nV$$

If the plates are sufficiently thick so that the hole aspect ratio t/d becomes large, the vortices that are produced at the sharp inlet edge will have time to roll up inside the tube, and provide a class I feedback when shed. This mechanism is characterised by the plate Strouhal number but is unlikely to be dominant in a hole tone whistle due to the low t/d ratio.

These three groups influence the whistling frequency, and may be expected to interact. If the feedback frequency matches the hole Strouhal frequency in any mode, the whistle may be expected to deliver large sound intensities. On either side of that frequency, the strong class II feedback in the cavity will dominate the weak class I feedback of the vortex shedding, modifying the shedding frequency to suit. However, a less energetic shedding is expected so that the whistle sound intensity would be lower. Moving the feedback frequency further away from the hole Strouhal frequency will eventually leads to a different wave mode (ie. a change in the value of n) to be assumed by the sound

feedback standing wave, causing a large frequency jump or the whistling to cease all together.

For the whistle to sound, the flow through hole 5 must be such that vortices are shed. The flow is characterised by the Hole Reynolds number:

$$Rh = \rho d_h V/\mu$$

In which and are respectively the density and viscosity of the liquid.

The Reynolds number describes the behaviour of the flow going through the hole, and the characteristics of the associated disturbance, which governs the separation of the flow at the sharp lip of the inlet or the outlet, and the stability of the shed vortex train. Assuming that t/d is small (≤1), for Rh≈1, no separation will occur, and no vortex is produced. For Rh≥15, a marked separation occurs, leading to the formation of a vortex. This vortex becomes more and more energetic with increasing Rh, but viscous damping prevents vortex shedding up to Rh≈50 even for lower values of t/d. Higher values of Rh lead to a steady vortex shedding and roll up providing the desired instabilities. Up to Rh≈2000, the vortex sheet should remain coherent and periodic. Raising the value of Rh further brings the flow into the transitional regime, when the flow changes from its laminar state to its more unsteady turbulent state. This leads to a broader spectrum of vortex shedding frequencies, making the sound produced by the whistle less tonal unless a more discriminating feedback process is employed. Nevertheless, whistles running at these high Reynolds numbers still produce well defined frequencies and provide an improvement in the spread of droplet sizes produced by a nozzle.

The flow between the plates 5, 5a should be such that the jet of liquid remains stable and well-defined as it passes through the surrounding liquid. Thus, for the core of the jet to remain laminar, the jet Reynolds number Rb = bv/μ should be less than 3000 and the jet aspect ratio b/d typically should be less than 10. To avoid vortex roll-up with the hole 5, the hole aspect ratio t/d should be less than 3, and furthermore to minimise irregularities in the development of the jet and the introduction of the spurious noise the surfaces of the

holes should be as smooth as reasonably possible, for example such that the roughness Reynolds number:

$$R_\epsilon = \rho \epsilon V/\mu \leq 50$$

where ϵ is the maximum surface roughness.

Indeed a good quality of surface finish is indicated for all flow passages of the apparatus.

Figures 4, 5 and 6 show in more detail apparatus according to the invention which employs a hole-tone whistle. The device, intended to be capable of producing a substantially monodisperse spray, but also operable off its design-point, comprises a generally cylindrical body 10, closed at one end by a hemispherical cap and at the other by the assembly generally indicated as 14.

A connector 16 is mounted upon body 10 and communicates with its interior 18. Adjacent its lower end, body 10 contains a cylindrical plunger 20, carried by rod 22 and provided with an O-ring seal 24. A cylindrical cavity 26 within plunger 20 communicates via a bore 28 in rod 22 with an orifice 30, which opens into body interior 18. Cavity 26 is closed at its lower end by plate 32 with a central aperture 34.

Rod 22 passes through cap 12, and is axially movable by means of the assembly generally indicated at 40, comprising a rotatable cap 42 which is attached to the outer end of rod 22 by screw 44, and threaded upon fixed bush 46, carried by mount 48 attached to cap 12. O-ring 50 mounted within bush 46 surrounds and seals rod 22. Axial adjustment of rod 22 provides axial adjustment of plunger 20 within cylinder 10.

Assembly 14, which closes the other end of cylindrical body 10, comprises a plate 50 with a central aperture 52 of the same chameter as aperture 34, and a plate 54 with a central configured nozzle orifice 56. Plates 50 and 54 are carried by plate support members 58 and 60 respectively, which are assembled together with plates 50 and 54 by means of screws 62, the whole being mounted by screws 66 upon annular carrier member 64, itself secured in a liquid tight manner to the lower end of body 10.

Plate 32, plate 50 and plate 54 are mounted such that aperture 34, aperture 52 and the nozzle orifice 56 are in axial alignment, providing communication from cavity 26, through the aligned apertures 34 and 52,

and the nozzle orifice 56, to the opening 68 in plate support member 60.

In operation the liquid which is to be distributed as a spray is fed under pressure through connector 16 to the interior 18 of body 10, O-ring seals 22 and 50 preventing leakage of the liquid between plunger 20 and the interior wall of body 10, and through fixed bush 46. Liquid under pressure passes into bore 28 through orifice 30 and enters chamber 26 within plunger 20.

Liquid from chamber 26 then exits chamber 26 through calibrated aperture 34 into chamber 35. The position of plate 32, and hence aperture 34, is adjusted relative to plate 50, and hence aperture 52, by means of rotatable cap 42, plunger 20 and rod 22, to achieve positive feedback conditions within chamber 35. Apertures 34 and 52, together with the intermediate chamber 35 constitute a hole-tone whistle, under which energy is extracted from the liquid flow through chamber 35 and converted into an acoustic vibration.

Leaving chamber 35 though aperture 52, the liquid enters chamber 53 and leaves it as a jet from nozzle orifice 56 in plate 54, entering the surrounding atmosphere where the acoustic energy generated within chamber 35 and conveyed to the jet through the liquid promotes controlled break-up of the jet, ideally into a monodisperse spray.

The principal dimensions of the apparatus, and its working parameters, when operating with water or an aqueous solution having substantially the fluid properties of water, are as follows:

d_n	diameter of nozzle 56	0.3 mm
d_h	diameter of apertures 34, 52	0.4 mm
b	axial spacing of apertures 34, 52	0.5 mm
k	monodisperse droplet size	0.55 mm
S_n'	nozzle Strouhal number $(fd_n{}^3/Q)$	0.33
(hence $S_n = 0.26$)		
S_h'	hole Strouhal number $(fd_h{}^3/Q)$	0.78
(hence $S_h = 0.61$)		
fmax	monodisperse frequency	5200 Hz
Vn	flow velocity through nozzle 56	6.1 m/s
	flow velocity through whistle 34, 52	3.4 m/s
	spacing of aperture 52 and nozzle 56	2 mm
	overall diameter of apparatus	20 mm
Q	flow rate	0.43 ml/s

The dimensions of the chamber 53 may be chosen by experiment such that the acoustic vibrations in the liquid are directed towards the nozzle 56 rather than dispersed within the chamber. In this particular embodiment, because the value of S_h is at least twice the value of S_n for controlled jet break-up, the whistle hole 52 cannot serve as the spray nozzle, and therefore the additional nozzle plate with an appropriately sized nozzle 56 is necessary. However, in some circumstances if the properties of the working liquid permit, and the operating frequency is appropriate it may be possible to use the downstream whistle hole also as the nozzle especially if some departure from optimum performance can be tolerated.

The plate 54 is 0.8 mm thick and the nozzle is formed with a 60° conical inlet and parallel exit portion. Alternatively, a traditional bell-mouth shape is suitable, the objective being in both cases to avoid flow separation from the walls of the nozzle, and to minimise acoustic energy dissipation in the nozzles. The nozzle surface is as smooth as reasonably achievable consistent with cost, since the smoothness of the surface determines the level of disturbance at the jet surface and thus its aerodynamic drag. At very low flow rates the nozzle length becomes significant, necessitating a stronger acoustic signal to maintain controlled jet break-up.

The impedance of the nozzle should be chosen to match the flow rates, fluid properties and operating frequency or frequencies. A low impedance nozzle is desirable to minimise losses; if the nozzle is considered as containing a plug of liquid through which the acoustic vibrations must be transmitted, the inertial stiffness and viscous losses of the plug are both reduced by keeping the nozzle as short as possible, thereby reducing the impedance, at least at frequencies below or not more than about an octave above the resonant frequency of the plug. The acoustic transmission efficiency of the nozzle may also be adversely affected if the nozzle plate is too flexible; a converging nozzle as described in a rigidly mounted plate is preferred.

If the apparatus is required to operate at a single frequency, or in a narrow range of frequencies then the resonant frequency of the nozzle should be chosen accordingly, and moreover the chamber 53 should be likewise dimensioned so that its resonant frequency matches that of the nozzle. Then the acoustic pressure at the nozzle is raised, and transmission efficiency improved.

To achieve a monodisperse spray the whistle frequency must equal the frequency of the fastest-propagating capillary wave.

Since the nozzle Strouhal number:

$$S_n = d_n\ fmax/Vn$$

and the hole Strouhal number

$$S_h = d_h fmax/Vn$$

Then, assuming all the flow through the whistle also passes through the nozzle, eliminating the respective flow velocities V by reference to the constant volumetric flow rate results in:

$$S_h/S_n = (d_h/d_n)^3$$

Hence, since the likely effective range of S_n for controlled break-up is between 0.14 and 0.29, and preferably about 0.22, indicative values for both d_n and d_h may be obtained as a basis for experimental design.

Thus, for $S_n = 0.22$

$$d_h = 0.6/\sqrt[3]{S_h}$$

which for experimentally observed values of $S_h \approx 0.7$ gives

$$d_n = 0.6d_h$$

The value of S_n is characteristic of the working liquid and alone determines the operating characteristics of the nozzle 6 within a useful range of Reynolds number.

Furthermore, provided d_h and d_n are chosen appropriately and the whistle plate separation distance is adjusted to ensure adequate positive feedback at fmax, then since S_h and S_n remain approximately constant over a range of flow rates Q, the operating frequency of the whistle tracks the variation of fmax with flow rate within design limits.

For a chosen drop size, the flow delivery rate is controlled by the break-up frequency. The operational range is therefore linked to the ability of the whistle to generate a strong enough signal at the desired frequency. The energy available to the whistle is proportional to ΔP, the pressure drop across the whistle, while its acoustic efficiency is roughly proportional to $1/\Delta P$, which cancels it out. The sound energy is therefore mainly independent of flow rate. But a higher frequency signal of identical energy has a lower sound intensity, so the amplitude of the controlled disturbance δ_0 on the surface of the jet becomes smaller. Taking $\delta_0 = F\,[V]$, the break-up length of the jet z/d increases as a function of $V\ln(V)$, as a result of the increased jet velocity and of the reduced signal amplitude δ_0. This reduces the control of the jet breakup and the monodispersity performance deteriorates. For each operating environment, there will be a maximum value of z/d up to which varicose break-up dominates. In an extremely noisy environment (ie. an IC engine) or a very windy environment (ie. aircraft spraying), we expect the maximum value of z/d to be smaller than for a spray for domestic use. The maximum flow rate for which monodisperse drops are produced is

$$Q \le \pi/4 \sqrt{(\sigma d_n^{3}/\rho)}\ 1/\ln(d_n/2\delta_0)\ (z/d)\max$$

Regardless of the break-up length, the flow rate is ultimately limited by the quality of the whistle which can be manufactured economically as an increase in flow rate has a non-linear effect on the necessary manufacturing tolerances. The necessary higher frequencies are produced at higher flow rates and by a whistle with smaller length scales, which both require tighter tolerances and therefore are more

expensive to manufacture.

In terms of $R\epsilon$,

$$R\epsilon \leq 50$$

$$\text{or } \epsilon/d_h \leq 50/R_h$$

$$\text{and } Q \leq 34k\nu/(\epsilon/d_h)\sqrt[3]{Sd_h}$$

A possible method for alleviating this problem is to have nozzles running in parallel at lower frequencies, driven either by separate whistles or by a single common one.

Conversely, the lowest flow rate is achieved for the lowest frequency. If the lowest operational hole Reynolds number Rh ≈ 100 and the lowest possible hole Strouhal number $S_h \approx 0.5$, then:

$$d_h = \sqrt[3]{(S_h/S_n)}\ k/1.89$$

$$\text{and } Rh = 4Q/\pi\nu d \geq 1000$$

$$\text{or } Q \geq 550\nu k$$

For a typical spray with desired drop sizes of k = 300µm, supposing $S_h = 0.7$ independent of Rh, assuming that the liquid has the kinematic viscosity of water $\nu = 10^{-6}$ m²/s and that the nozzle is injection moulded allowing $\epsilon/d_h = 10^{-3}$ then:

$$0.1\text{ml/s} \leq Q \leq 9\text{ml/s}$$

$$\text{or } 0.6\text{l/h} \leq Q \leq 33\text{l/h}$$

Other types of oscillator than those already described may be used. Published literature relating to whistles operating on air or other gas may be used for guidance, provided that it is taken into account that to achieve a similar Reynolds number (Vd/ν) the flow must be fifteen times slower in water than in air, and that for a similar Mach number (V/c) the flow must be fifteen times faster. Thus, supersonic whistles are impracticable for use with liquids, and it will be appreciated also that in a class II or class III whistle operating with a liquid, the feedback is almost instantaneous.

In Figure 7, there is shown a Hartmann oscillator in which liquid passes through a convergent nozzle 70 into a tuned cavity 72 wherein pressure oscillations present in the liquid leaving the nozzle 70 are amplified to provide a pressure maximum at the entrance 74 to an exit duct 76. Pressure waves travel down the duct 76 and are utilised at a discharge nozzle (not shown) to produce a controlled-droplet spray.

The dimensions of the cavity 72 may be adjusted by means not shown to vary the tuned frequency. The port 78 introduces reactance into the system necessary for oscillations to be established and the device operates as a class III whistle.

In Figure 8 a relaxation oscillator operates as a class II whistle and comprises an inlet nozzle 80, flow from which impinges on a splitting edge 82 and is deflected alternately down one side 84 or the other 86, resulting in pressure fluctuations at the exit 87. Feedback ducts 88 communicate the pressure fluctuations back to a point just upstream of the edge 82, thereby to reinforce the alternate deflection of the flow.

Figure 9 shows a feedback oscillator in which the structure is similar to that of Figure 8, corresponding parts carrying the same reference numerals. However, instead of the feedback ducts 88 there is a continuous closed passage 90 which communicates at its ends 92, 94 with opposite sides of the main flow passage between the exit of nozzle 80 and the splitter 82.

The passage 90 is dimensioned such that the liquid therein is caused to oscillate at the same frequency as the pressure pertubations produced by the flow splitter 82, thereby reinforcing the alternation of the flow around the opposite sides thereof.

Figure 10 illustrates an edge-tone whistle in which liquid from a nozzle 80 impinges on the leading edge 82 of a tuned mechanical device 100, for example a beam. Flow is shed alternately around each side 84, 86 as described before, a resonant frequency of the beam 100 being tuned to match the shedding frequency, and to reinforce the pressure oscillations at exit 87. This type of whistle offers opportunities for extracting mechanical energy from the liquid, and to apply that energy where it will have most effect on the break-up of the jet, ie. at the spray nozzle.

Thus, in Figure 11, a nozzle assembly eg. for a hand-held spray comprises an inlet orifice 80 the flow from which impinges on a leading edge 82 of tuned member 100 and is deflected alternately on each side of it as already described, causing the tuned member 100 to vibrate about a nodal point coinciding with its mounting 102 in the structure 104 of

the nozzle assembly.

The liquid flow passes through a port 106 in the mounting structure into a chamber 108 and thence to atmosphere via a spray nozzle 110, forming a jet 112.

The spray nozzle 110 is partially defined by a portion 116 of the tuned member 100. The portion 116 transmits the resonant vibration of the member 100 to the liquid jet 112 as it exits the nozzle 110 causing it to break-up into droplets 114 of controlled size.

It will be appreciated that the member 100 may be configured to vibrate in other than the transverse flexural mode discussed. For example it could instead vibrate longitudinally of the axis 118 of the device. Also, it could completely define the nozzle 110 instead of only partially as shown in the drawings.

Alternatively, the member 100 may drive an airborne sound generator (eg. in the manner of a small loudspeaker cone or tweeter) to impart vibrations to the air in the region of the nozzle 110 whereby to transmit those vibrations to the jet of liquid as it leaves the nozzle. The sound generator could conveniently be arranged concentrically with the nozzle so that vibrations may be imparted both to the air and directly to the liquid as it passes through the nozzle, provided that the vibrations imparted to the liquid from the nozzle and via the air are maintained in phase with each other.

As has been stated, the jet of droplets need not be circular in cross-section. Thus Figure 12 shows sectioned side and end views of a divergent nozzle producing a conical liquid sheet. A casing 120 has a circular orifice in which a pin 122 is located. The edges 12 of the casing are angled to form a frustoconical annular passage 126 between the head 128 of the pin and the wall of the casing. When liquid is passed through the passage, it forms a conical sheet of liquid. The break up of this liquid sheet is susceptible to excitation in accordance with the invention, eg. by a whistle, leading to a better control of the produced spray.

Figure 13 is an end view of a modification of the liquid nozzle shown in Figure 12. In this embodiment, the pin 122 and the casing 120 define an annular passage 126 which has a sinuous profile about a base

circle. The sinuosity further controls the jet break-up by matching the wavelength of the nozzle sinuosity to the wavelength of the excitation frequency leading to the jet break-up.

The nozzles of Figures 12 and 13 need not be circular in section; other shapes eg. an ellipse can be adopted, and indeed the nozzle need not form a closed figure, and may be formed as an extended slot which may be straight as in Figure 2, or curved.

It further will be appreciated that whilst the specific embodiments have been discussed in the context of single-frequency whistles, it is possible that some applications may require a droplet size distribution best produced by more than one predetermined frequency. Thus it may be appropriate to employ a whistle which warbles (eg. which produces two frequencies which beat and result in an apparently-oscillating tone) or produces frequencies primarily within a narrow band. Indeed, the invention may be realised by any form of liquid oscillator in which the sound intensity at the desired frequency or frequencies is greater than at other frequencies, thereby promoting controlled break up of the spray.

Also, whilst the invention has been described in the context of the break up of single-phase liquid jets, it is contemplated that the controlled break up into droplets of controlled size of the liquid component of a two-phase flow from a spray nozzle may also be achieved by the concepts described herein. Such a flow comprises a liquid component plus a vapourising or gaseous propellant (eg. as in some domestic aerosols) and the term "liquid" as used herein includes such a two-phase fluid.

CLAIMS

1. A method of generating a spray of liquid droplets comprising establishing a flow of the liquid, forming the flowing liquid into a jet, and subjecting the jet of liquid to vibrations of at least one predetermined frequency which promotes the break-up of the jet into droplets, characterised in that the energy for the vibrations is obtained from the liquid.

2. A method as claimed in Claim 1, wherein the energy is obtained from the kinetic or pressure energy of the liquid.

3. A method as claimed in Claim 1 or 2, corresponding generating said vibrations by inducing hydrodynamic oscillations in the liquid flow.

4. A method as claimed in any preceding claim, wherein the vibrations are induced in the liquid as or before it is formed into a jet.

5. A method as claimed in any preceding claim wherein the frequency is substantially a pure tone.

6. A method as claimed in Claim 5, wherein the vibration frequency and liquid flow rate are matched such that the vibration frequency is at or near to an unstable break-up frequency of the liquid jet, whereby the spray is substantially monodisperse.

7. Apparatus for generating a spray of liquid droplets comprising means for receiving a flow of liquid and for forming the liquid into a jet, and means for generating vibrations in the jet using energy obtained from the liquid, the vibrations being of at least one predetermined frequency such as to promote break-up of the jet into droplets.

8. Apparatus as claimed in Claim 7, wherein the means for generating vibrations is adapted to utilise the pressure or kinetic energy of the liquid.

9. Apparatus as claimed in Claim 7 or Claim 8, comprising a nozzle for forming the jet and a hydrodynamic oscillator disposed upstream of the nozzle for generating the vibrations.

10. Apparatus as claimed in any of Claims 7 to 9, wherein the means for generating the vibrations is adapted to produce a substantially pure tone.

11. Apparatus as claimed in any of Claim 7 to 10, wherein the means for generating vibrations is such as to produce a predetermined frequency which varies with the flow velocity of the liquid.

12. Apparatus as claimed in any of Claims 7 to 10 wherein the means for generating vibrations is such as to produce a substantially constant frequency, means being provided for adjusting the flow velocity of the liquid.

13. Apparatus as claimed in Claim 7, comprising means for extracting energy from the liquid flow and for reintroducing it into the liquid to generate the vibrations.

14. Apparatus as claimed in Claim 13, wherein the means for extracting energy comprises a tuned mechanical device.

15. Apparatus as claimed in Claim 14, wherein the means for forming the liquid into a jet are at least partially defined by the tuned mechanical member, or by structure connected thereto.

16. Apparatus as claimed in Claim 14 or 15, wherein the means for extracting energy is a resonant part of an edge-tone whistle.

17. Apparatus as claimed in any of Claims 13 to 16, comprising means for at least partially reintroducing the energy into the liquid via the air or other gas through which the liquid passes after being formed into a jet.

18. A method of generating a spray of liquid droplets substantially as herein described with reference to the accompanying drawings.

19. Apparatus for generating a spray of liquid droplets substantially as herein described with reference to and as shown in any of Figures 4 to 11 of the accompanying drawings.

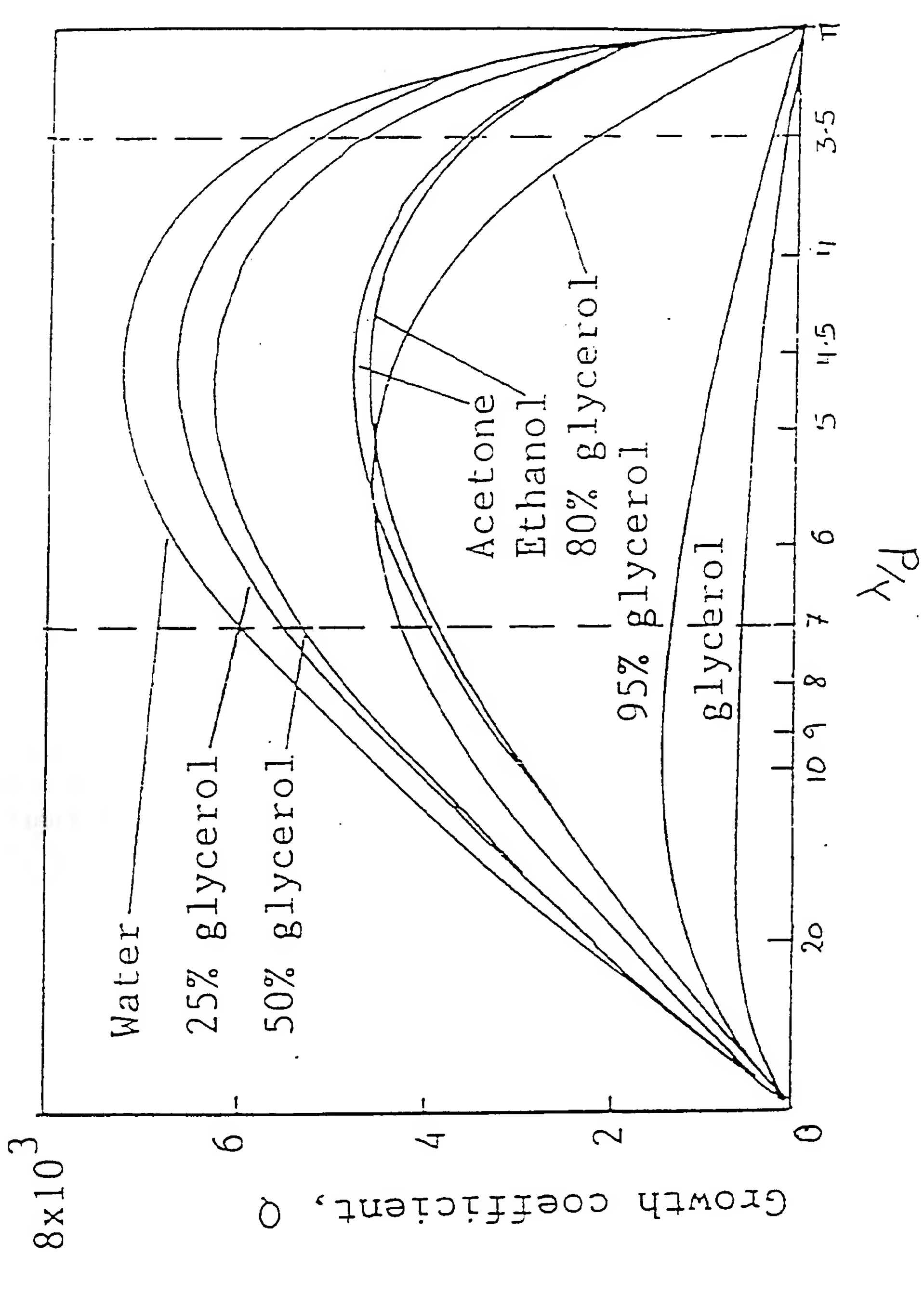

Figure 1 The Dependence Of The Varicose Mode Growth Coefficient, Q, On Viscosity

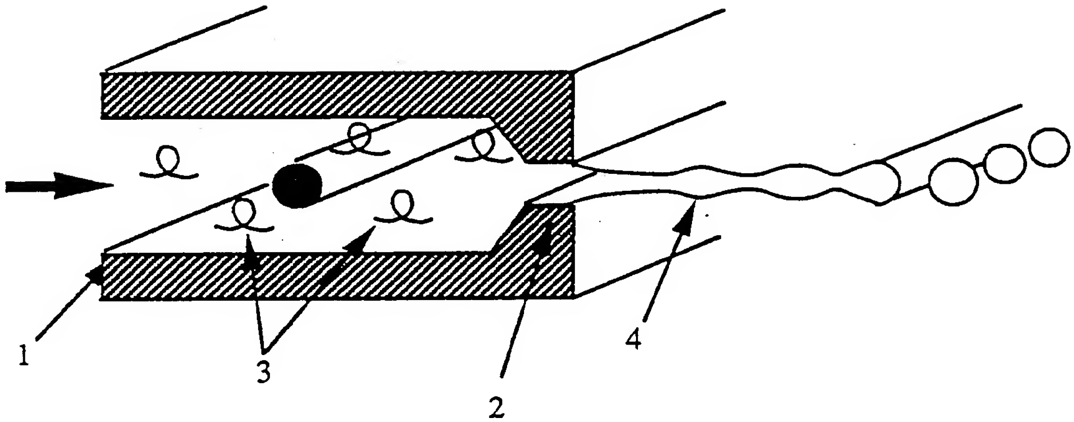

Figure 2

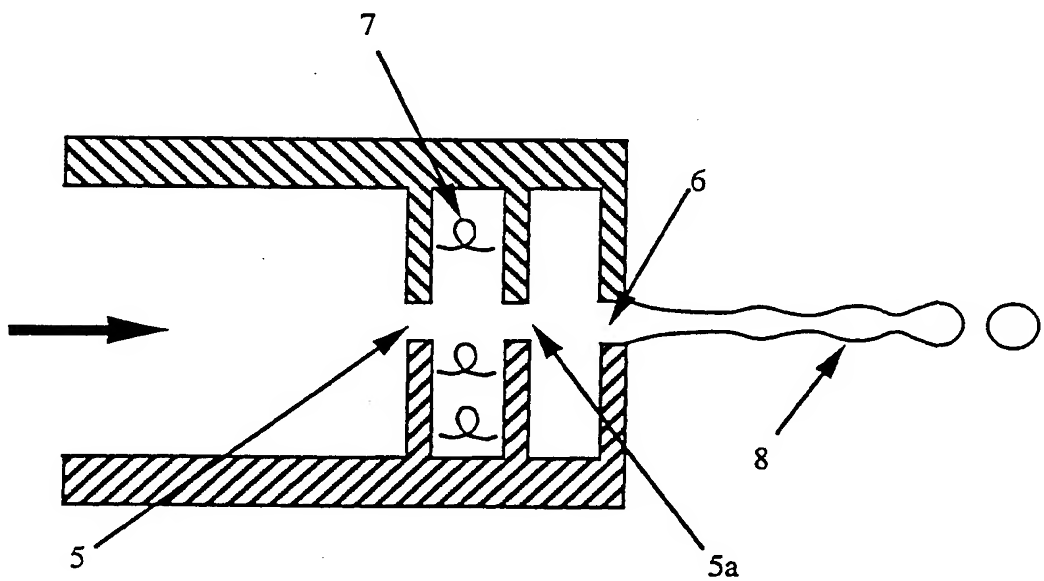

Figure 3

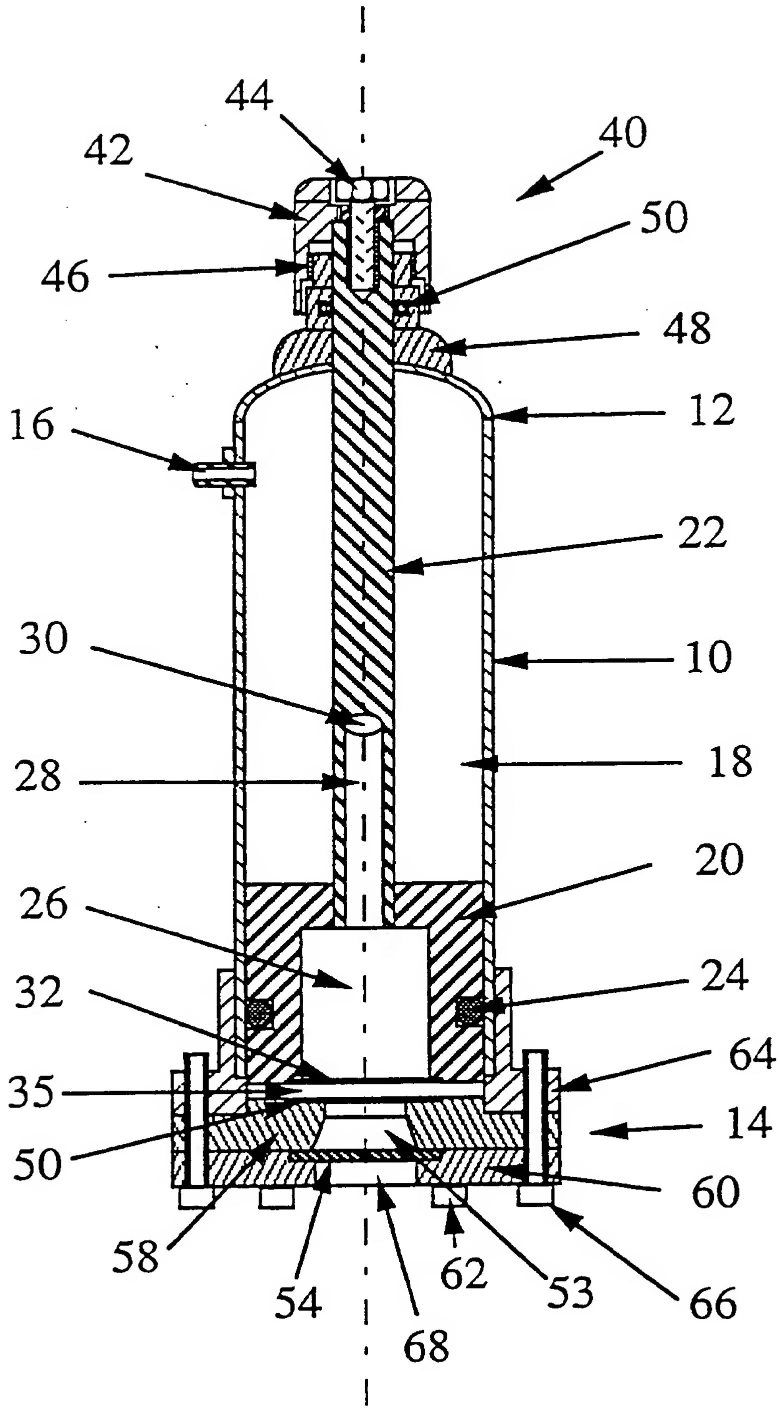
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Figure 4

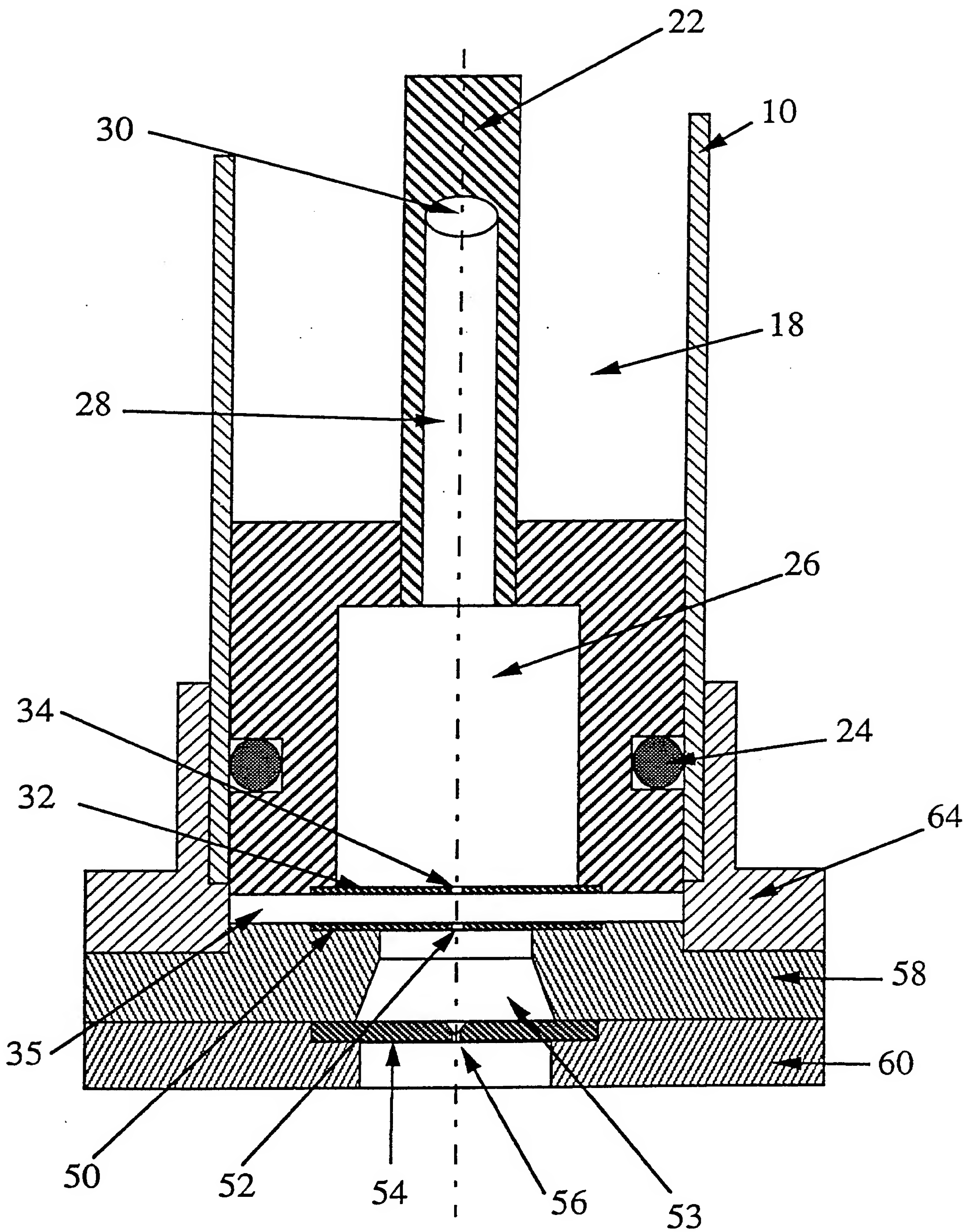

Figure 5

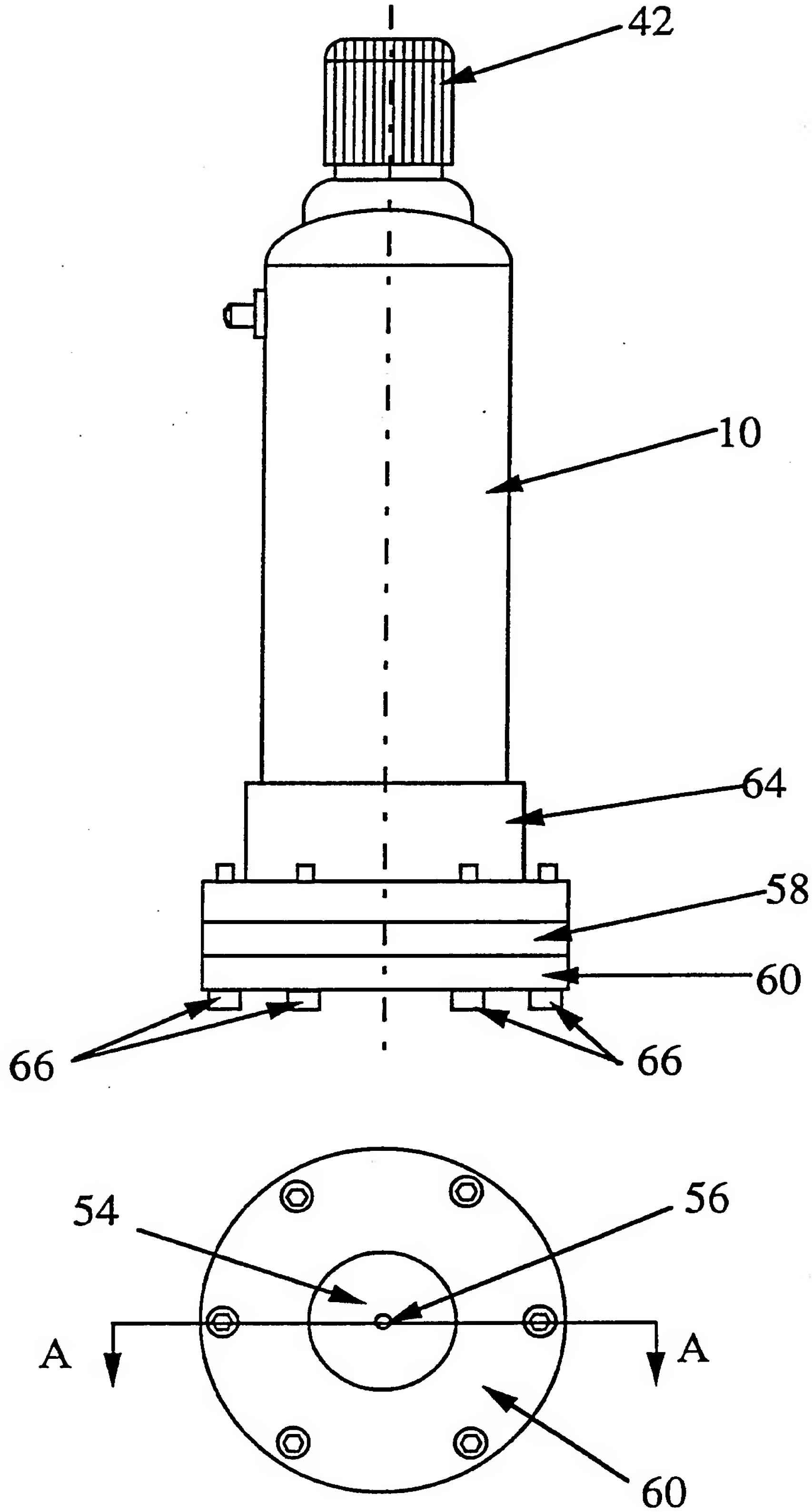

Figure 6

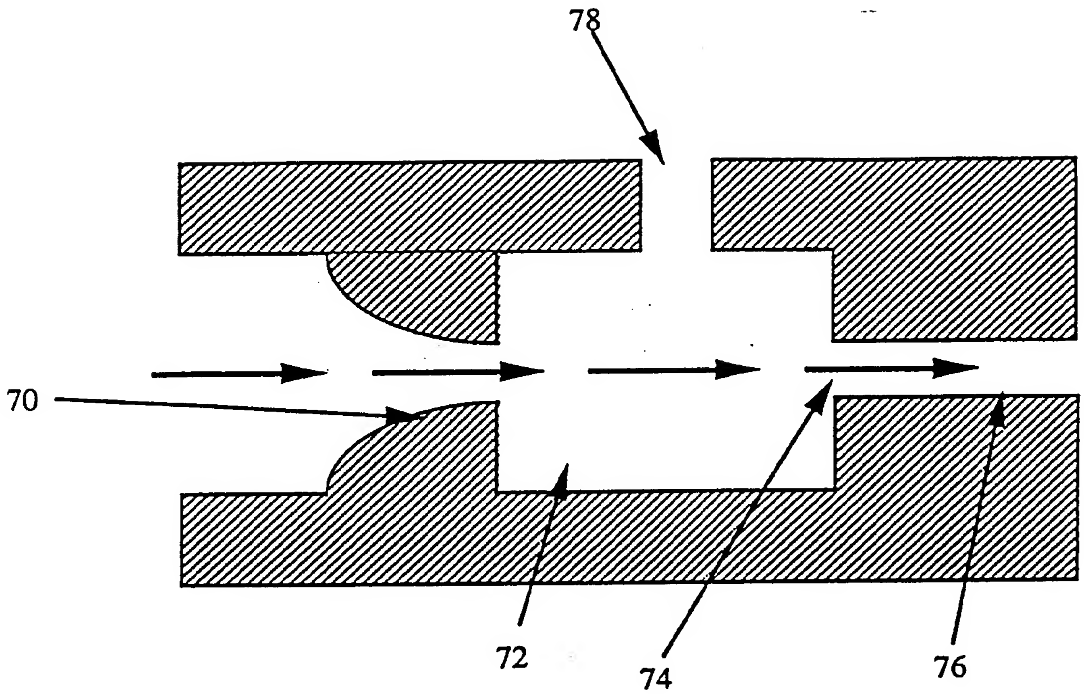

Figure 7

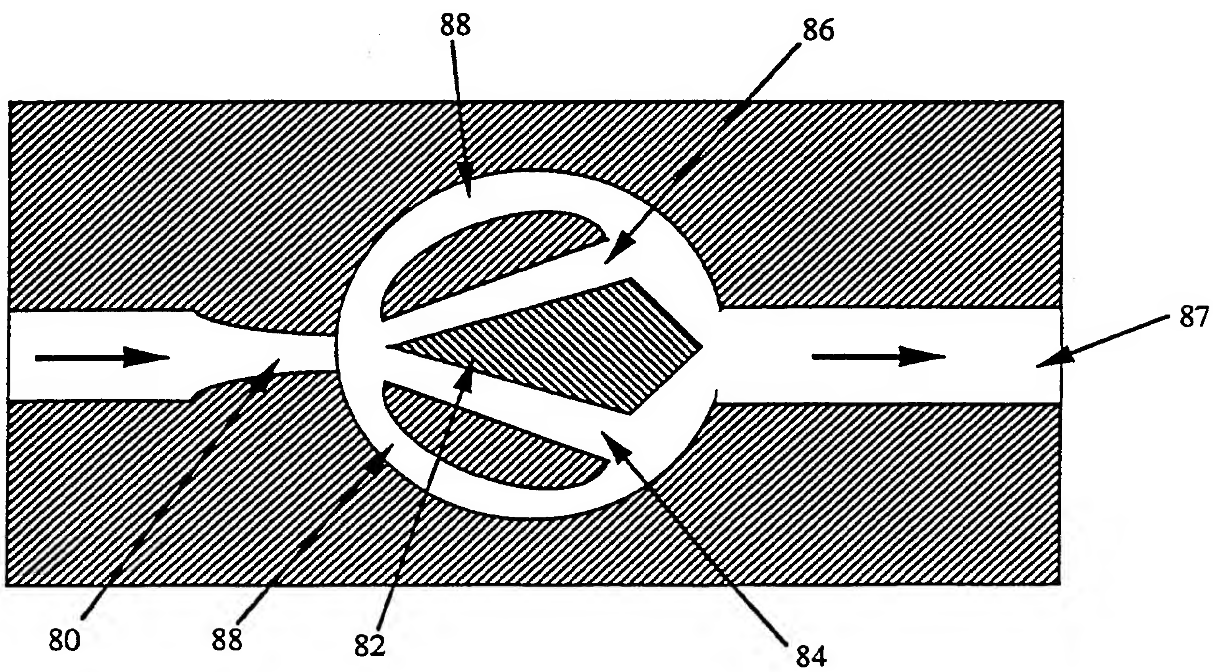

Figure 8

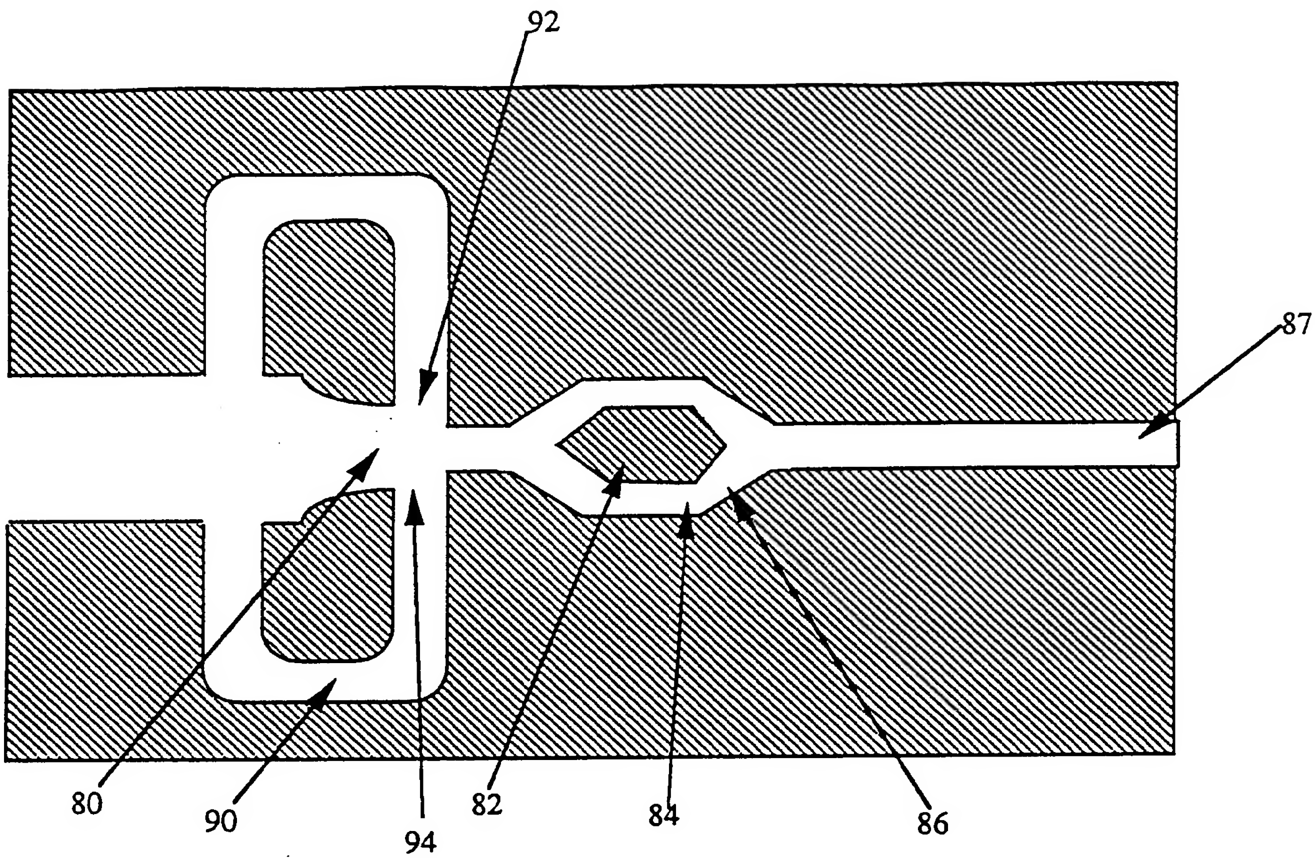

Figure 9

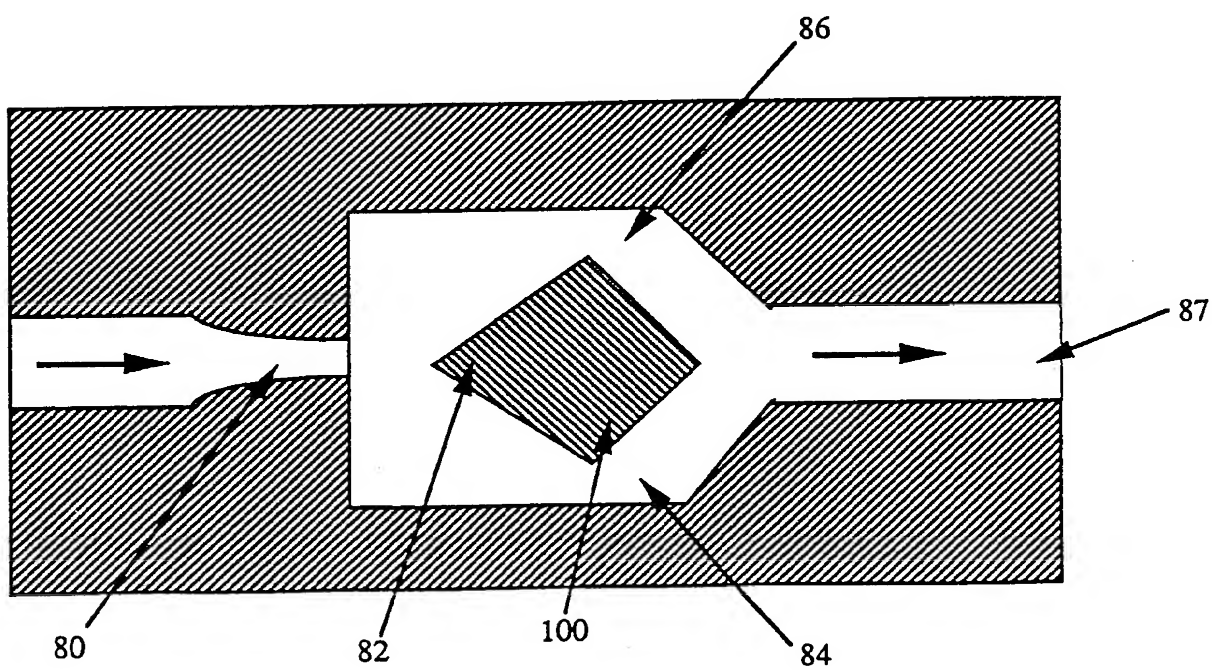

Figure 10

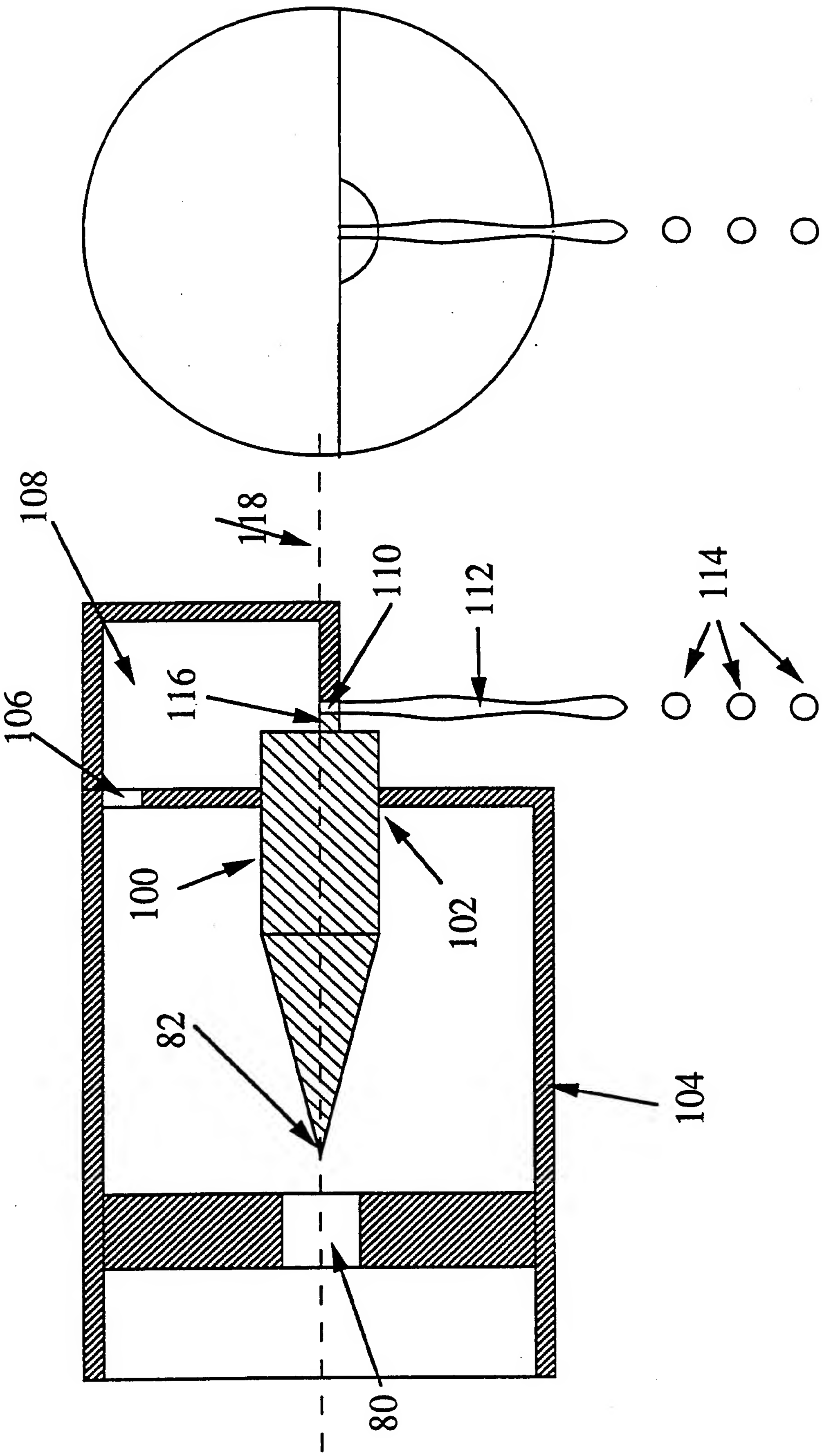

Figure 11

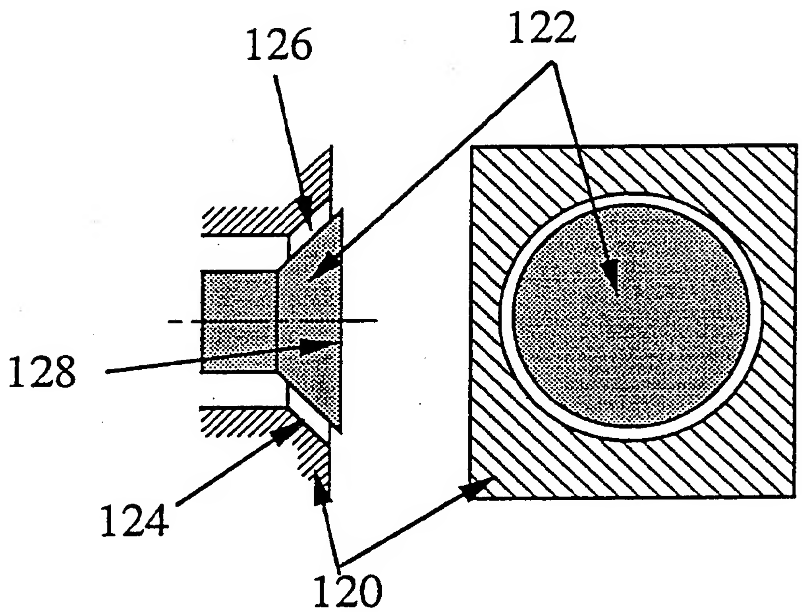

Figure 12

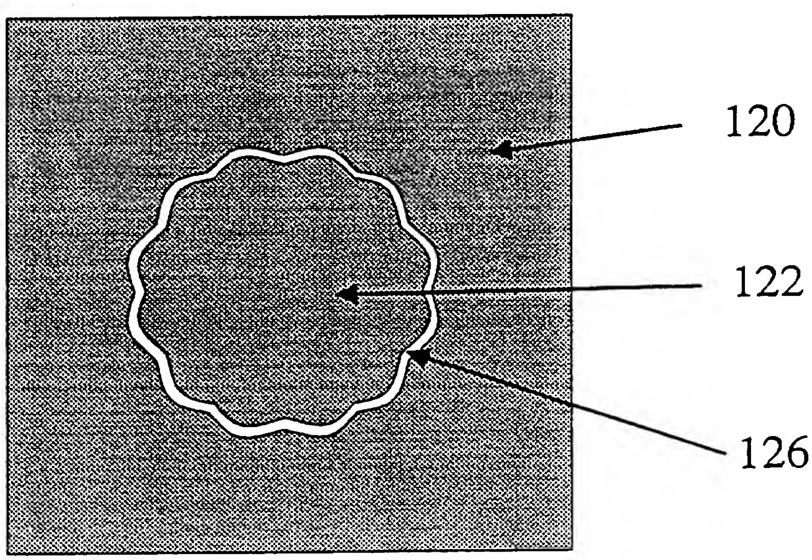

Figure 13

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 93/01089

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 B05B1/08

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	B05B

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category°	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	US,A,3 776 460 (FICHTER) 4 December 1973 see the whole document ---	1-4, 7-12,18, 19
A	J.ACOUST.SOC.AM. vol. 65, no. 5, May 1979, USA pages 1140 - 1142 HASAN M A Z; HUSSAIN A K M F 'a formula for resonance frequencies of a whistler nozzle' ---	1,5,7
A	EP,A,0 305 996 (WOODS) 8 March 1989 see claim 2; figure 3 ---	13
A	US,A,4 562 867 (STOUFFER) 7 January 1986 see the whole document -----	1,7

° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

1

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
28 SEPTEMBER 1993	01. 10. 93
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	GUASTAVINO L.

Form PCT/ISA/210 (second sheet) (January 1985)

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

GB 9301089
SA 74403

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 28/09/93
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-3776460	04-12-73	None		
EP-A-0305996	08-03-89	US-A-	4905909	06-03-90
		AU-A-	2174788	02-03-89
		DE-A-	3870103	21-05-92
		JP-A-	1145406	07-06-89
		US-A-	4955547	11-09-90
US-A-4562867	07-01-86	None		

EPO FORM P0479

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82